Real-Time In Situ Measurements for Earthquake Early Warning and Spaceborne Deformation Measurement Mission Support

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Abstract— **The primary goal of our AIST project is to provide the most accurate and timely early warning information on global geological hazards to first responders, scientists, mission planners and policy makers. The primary mission of focus is NASA's Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission. Specifically our objectives are as follows: (a) Develop a publicly available real-time ground deformation data system fusing two in situ network data sources: low latency (1 s) high-rate (1 Hz or greater) CGPS & traditional ultra-high-rate (100 Hz) seismic data (accelerometers); (b) Enable rapid access to absolute displacement waveforms, replay capability, and modeling of significant events related to global geological hazards; (c) Enable detection and preliminary modeling of signals of interest by the dense ground networks, which will help mission planners exploit less-frequent but higher resolution InSAR observations; (d) Use GPS data products to calibrate InSAR measurements for atmospheric and orbital errors, significantly increasing the accuracy of interferograms. The first three objectives relate to early warning systems for mitigation of natural hazards, including earthquakes, volcanic activity, tsunamis, landsliding and flooding, and further rapid response after these types of events such as earthquake magnitude estimation, slip modeling, and transient detection. The fourth objective is specific to using ground GPS networks to reduce tropospheric refraction effects and satellite orbital errors in Interferometric Synthetic Aperture Radar (InSAR) analysis. The common theme for the entire project is to use existing in situ geophysical monitoring networks (geodetic and seismic) to respond quickly to anomalous crustal deformation to mitigate losses due to natural hazards, and to guide space mission planners in planning for follow up InSAR measurements. Once the InSAR measurements are taken, then the in situ GPS networks can be used to calibrate the InSAR images. Another common theme is to use data access points (GPSE-AP's) to the GPS Explorer data portal developed under a NASA MEaSUREs project (*Webb et al.*, 2009) and NASA's contribution to the EarthScope project to allow users to access the deliverables of the project, to interact with geodetic, seismic, and atmospheric databases, and to store results (data and revised metadata) in the underlying SOPAC databases. Finally, the tools developed here are designed to improve data and metadata quality to reduce erroneous detection of anomalous deformation ("false alarms").**

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I. Earthquake Early Warning

The earthquake early warning (EEW) architecture is shown schematically in Fig. 1. The assumption is that real-time high-rate (e.g., 1 Hz) GPS raw data are available directly from real-time GPS stations (e.g., through UCSD's HPWREN communications) and/or from real-time GPS servers (e.g., USGS; UNAVCO/PBO). Further, we assume that real-time software controls the flow of data and computes on-the-fly displacements. For this project, we use Geodetic, Inc. RTD software licenses available at UCSD. A further (optional) assumption is access to real-time very-high-rate (e.g., 100 Hz) accelerometer data from seismic data servers (e.g. CISN) streaming mSEED format, a standard seismic data format for velocity and acceleration data. For this project, we have developed 4 distinct software modules for EEW, the first three developed at SIO and the fourth developed at Caltech. The modules are described below.

A. Network adjustment

This module takes displacements (in RYO format) from overlapping GPS sub-networks and adjusts them to produce a single stream of displacement data (in RYO format) from the entire network, relative to the true-of-date coordinates of a specified fixed station in the network. The algorithm is described in Crowell et al. (2010) and Bock et al. (2011). RYO is an open binary format designed to stream real-time high-rate displacements.

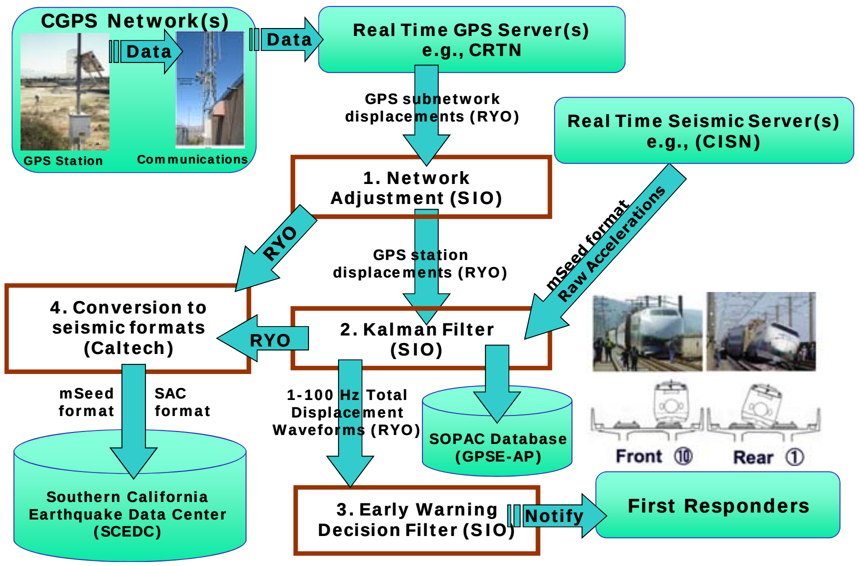

Figure 1. System architecture for earthquake early warning (EEW), including 4 modules (labeled) developed for this project.

B. Kalman Filter

This module takes high-rate (e.g., 1 Hz) displacement waveforms from a single GPS station and combines them with very-high-rate raw (e.g., 100 Hz) accelerometer data, to produce a very-high-rate displacement waveform record. A forward filter can be used for real-time estimation (delay of 1 second). A smoothing filter can be used for near-real-time estimation (delay of several seconds). The basic algorithms are described in *Bock et al.* (2011).

C. Early warning decision filter

This module takes a very-high-rate displacement waveform record constructed from GPS displacement and raw accelerometer data and decides whether a threshold level has been exceeded. This can be done on a site by site basis using displacements or in a network approach using strain changes in triangular elements as described in *Crowell et al*. (2010). Once an anomalous detection is made, there are further options to use the coseismic (static) displacements to compute rapid earthquake magnitude estimates, centroid moment tensor solutions, and preliminary slip models of earthquake rupture. Examples from the 2010 Mw 7.2 El Mayor-Cucapah earthquake are given in *Bock et al.* (2011).

D. Conversion to seismic formats

This module contains several software elements. The first element *getgps* listens to an IP port at SIO and copies on-the-fly GPS and/or GPS/Seismic displacement waveforms into a staging pool at the Southern California Earthquake Data Center (SCEDC). The second element *ryo2mseed* converts the native RYO format to seismic mSEED format. The third element *archiveGPS* takes new mSEED files and copies them to the SCEDC waveform archive and database, making these waveforms searchable. The fourth element *STP* is a client application that retrieves waveforms from the SCEDC archive for the user. The waveforms are also stored in seismic SAC format.

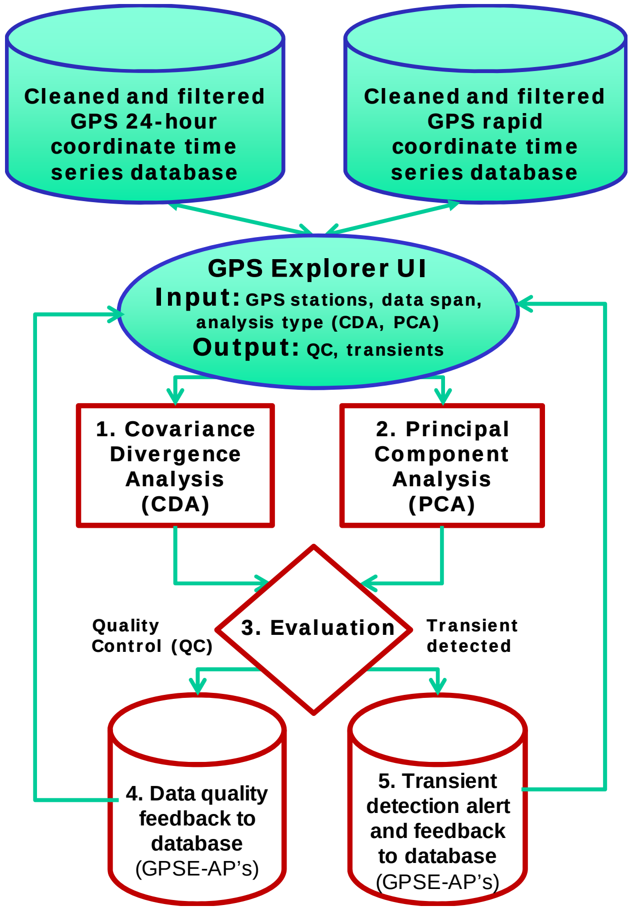

Figure 2. System architecture for quality control and transient detection, including 5 modules developed for this project.

II. Transient Detection and Quality Control

We have begun implementation of transient detection methods for data quality control and deformation anomalies, including Covariance Descriptor Analysis (CDA) and Principal Component Analysis (PCA). These methods enable detection and preliminary modeling of signals of interest by dense ground (in situ) networks to help mission planners exploit less-frequent but higher resolution InSAR observations. Furthermore, they can be used for enhanced quality control for GPS data products and metadata. The detection methods are designed to be applied to two data products: daily (24-hour) position time series from GPS combination solutions at JPL and SIO. These are available from the MEaSUREs project with a delay of 1-2 weeks or data collection; Re-processed high-rate (1 Hz) data from the EEW portion of this project at various averaging windows (e.g., 30 minutes, 1 hour, 24 hours). These are available within 1-2 days of data collection. The products and detection modules are controlled through GPS Explorer access points (GPSE-AP's).

The two techniques examine the data in fundamentally different and complementary ways. They are completely independent of each other in origin, logic and implementation. PCA detects common fundamental modes of ground motion across the array, and CDA detects statistically significant common anomalies in a space-time "image" composed of deformation time series. Both techniques have shown promising results in detecting synthetically introduced anomalies into time series deformation data. The two techniques were developed as part of JPL's participation in the Southern California Earthquake Center (SCEC) community transient detection exercise. Thus, the methods have been tested and fine-tuned for deformation transient detection.

The deliverable is broken down into five distinct modules (Fig. 2). Based on these, weekly PCA and CDA plots for the time series will be produced and made publicly available through GPS Explorer. Both techniques will be adjusted and refined as we gain more experience looking at real data sets.

A. *Covariance Descriptor Analysis (CDA)*

This module relies on a class of methods includes relatively recent technologies that have seen considerable success in the field of computer vision, and are predominantly used to detect statistically significant, spatially correlated anomalies in images.

B. *Principal Component Analysis (PCA)*

This module has been successfully implemented in tectonic geodesy for regional filtering and common mode removal.

C. *Evaluation*

This module examines the output of the CDA and/or PCA analyses, as specified by the user. There are two possible outcomes, including quality control (QC) and transient detection.

D. *Data Quality Feedback*

This module transfers reports on data of questionable quality back to the user, who can then choose to feed this information back into one or both of the coordinate time series databases.

E. *Transient Detection Feedback*

This module transfers any transient detection results back to the user, who can then choose to feed this back into one or both of the coordinate time series databases.

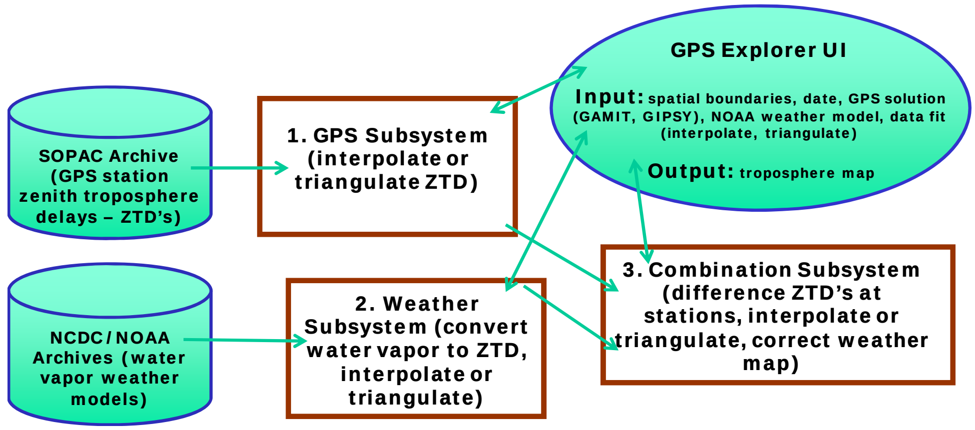

Figure 3. System architecture for quality control and transient detection, including 3 modules (labeled) developed for this project.

III. GPS/Weather Map InSAR Calibration

A primary objective of this project is to GPS data products and weather models to calibrate InSAR measurements for atmospheric and orbital errors. The goal is to significantly increase the accuracy of interferograms.

Through a GPS Explorer access point, the user specifies the spatial boundaries, date, and data fit method (interpolation or triangulation) for generating a troposphere correction map. In addition the user specifies the GPS solution source (GAMIT or GIPSY) and the weather model to be used (optional). The selection is then fed through three distinct modules (Fig. 3).

A. GPS Subsystem

This module accesses the SOPAC archive to extract the zenith troposphere delays (ZTD's) from GPS stations within the chosen spatial boundaries and date. It then creates a troposphere map using the chosen data fit method.

B. Weather Subsystem

This (optional) module accesses the NOAA or NCDC archives to retrieve water vapor models (NAM, RUC, NARR) for the region and date specified. Weather model precipitable water vapor is converted to ZTD, and a troposphere map is created using the chosen data fit method (triangulation or interpolation).

C. Combination Subsystem

If the user specifies the use of GPS and weather models, this optional module combines GPS and weather model data such that the GPS ZTD value is reproduced at the locations of the GPS stations, and a triangulated or interpolated troposphere map is created for the region.

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References

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